N94-15553

LASER TRACKING FOR VERTICAL CONTROL

Peter Dunn and Mark Torrence, Hughes STX Corp.,Lanham,MD
Erricos Pavlis, Univ. of Maryland,College Park,MD
Ron Kolenkiewicz and David Smith, GSFC LTP,Greenbelt,MD

ABSTRACT

The Global Laser Tracking Network has provided LAGEOS ranging data of high accuracy since the first MERIT campaign in late 1983 and we can now resolve centimeter-level three dimensional positions of participating observatories at monthly intervals. In this analysis, the station height estimates have been considered separately from the horizontal components, and can be determined by the strongest stations with a formal standard error of 2 mm. using eight years of continuous observations. The rate of change in the vertical can be resolved to a few mm./year, which is at the expected level of several geophysical effects. In comparing the behavior of the stations to that predicted by recent models of post-glacial rebound, we find no correlation in this very small effect. Particular attention must be applied to data and survey quality control when measuring the vertical component, and the survey observations are critical components of the geodynamic results. Seasonal patterns are observed in the heights of most stations, and the possibility of secular motion at the level of several millimeters per year cannot be excluded. Any such motion must be considered in the interpretation of horizontal inter-site measurements, and can help to identify mechanisms which can cause variations which occur linearly with time, seasonally or abruptly.

INTRODUCTION

LAGEOS laser ranging measurements have added significantly to our knowledge of horizontal motion at the observing stations and have helped to improve models of tectonic processes and regional deformation at plate boundaries (Frey and Bosworth,1988). The tectonic movements are as large as 17 cm/year between fast moving stations such as Huahine and Easter Island which lie astride the Pacific/Nacza plate boundary. The SLR data have demonstrated their ability to measure centimeter per year motions to a few mm/year, but geodesic lengths have usually been used in this work because they directly provide horizontal rates and are independent of vertical variations. The time grain of the horizontal measurements has progressed from annual values (Christodoulidis et al.,1985) to quarterly averages (Smith et al.,1990) as the network has grown and observation and force models have improved.

Accurate vertical control can assist the horizontal positioning in monitoring tectonic processes and the detection of pre- or post-seismic events. Accurate height determination also allows the measurement of post-glacial rebound and the investigation of atmospheric pressure loading at the stations. The scale of an Earth-centered reference system can be defined in a network of SLR stations to establish a global vertical datum. The systems can also be employed to calibrate altimeter instruments by determining the radial component of the orbit of the altimeter mission.

Degnan(1985) has described the various technical methods of accurate range measurement which include careful calibration for electronic path delays and atmospheric refraction, as well as accurate surveys of the distance between a system's electro-optical center and a ground bench-mark. Any systematic errors in the original observations will be preserved in the normal points which we employ in our analysis, and will affect the final position estimates for the stations. Characteristics of each instrument's laser transmitter and detection system must be monitored to ensure that the distribution of satellite returns is normally distributed. Any skewness in the range pattern would bias the normal points, and would usually be caused by errors which would delay the detection of the return, yielding normal points with a longer range value than that from a Gaussian distribution, although this system characteristic will vary with the detection scheme. The magnitude of the signature of the satellite retro-reflector array on the range measurement will also depend on the instrument. We have adopted a value of 251 mm. (Fitzmaurice et al.,1977) for the correction for the offset between the satellite's center-of-mass and its reflecting surface, which would be expected from the multiple photon, leading edge detection MOBLAS systems. Lower power transmitters with alternative detection methods may require corrections differing by a few millimeters.

Errors in station time-keeping can degrade the resolution of the horizontal component of station position, although modern systems using GPS time transfer for epoch time are synchronized to the microsecond, which is an insignificant error at the level of positioning accuracy currently dominated by errors in the satellite perturbation model. Systematic errors in the round-trip time measurement for range are more difficult to control. They will tend to cancel out in the horizontal position measurements of stations with adequate sky coverage, but will directly affect their height estimates. In this treatment we have restricted our analysis to the best calibrated observatories in the network, and have subjected their observations to particularly strict quality control standards. The locations of these stations are shown on the world map of Figure 1, and their positions listed in Table 1, with particular emphasis on the vertical component. The observations from these strong stations now allow us to reduce the interval for determination of 3-dimensional positions from a quarter of a year to a month, and thus provide improved resolution of the rate of any station movement.

DATA ANALYSIS METHOD

In our analysis, each SLR measurement constrains the solution of a numerically integrated satellite trajectory. A system of equations which satisfies all of the range information in a least squares sense is developed (Putney,1990) for orbits independently computed with an accurate perturbation model over time spans of approximately a month. The resulting linear system is subsequently solved to yield monthly three-dimensional coordinates of the tracking station positions, together with other geodetic parameters estimated at various time intervals. The motion of the satellite is computed in a reference frame which includes the effect of general relativity about the Earth with an adopted value of 398600.4415 km3/sec2 for GM, the product of mass and gravitational constant (Ries et al.,1992). The GEM-T3 geopotential model (Lerch et al.,1992) with expanded ocean tides to include significant LAGEOS perturbations was supplemented by third body perturbations from the sun and the moon, together with the planets Mercury through Neptune.

The effects of thermal drag on the satellite were represented by a model of the Earth Yarkovsky effect (Rubincam,1990) with an initial satellite spin axis orientation of 22 degrees, decreasing by 50% every 6 years. To satisfy remaining unmodelled orbit effects, a secular along-track acceleration was adjusted every 15 days, as well as the phase and amplitude of an along-track component acting once per revolution of the orbit. This once per revolution adjustment parameter is related to the eccentricity excitation vector described by Yoder et al.(1983) and has been found to accommodate variations in the behavior of LAGEOS which have not yet been adequately described (cf. Eanes et al.,1991). The values of secular along-track acceleration determined by the full network over the experimental period is shown in Figure 2. This is a well-determined parameter with a formal uncertainty of about .1 picometer/sec2, and the regularly repeating patterns in the early part of the signature have been modelled by several workers (Anselmo et al.,1983; Afonso et al.,1989; Scharoo et al.,1991) using theories based on both Earth-reflected and direct solar heating. The unusual behavior of the along-track signature commencing in 1990 is not very well predicted by these models.

Figure 3 shows the orthogonal components of the once-per revolution acceleration estimates, which are more weakly determined than the direct effect, and have formal errors of about the same size as a typical value. The cosine function of orbital angle from equator crossing measures unmodelled perturbations in the equatorial plane, particularly those associated with solar position and radiation pressure. The unusual variation in it's amplitude indicates a change in the satellite's behavior in 1989 and again in 1991, and recent observations have shown that the irregular behavior continues in 1992. Bertotti and Iess (1991) have suggested that torques on the spacecraft due to eddy currents and gravity gradient would lead to chaotic spin dynamics in 1991 or 1992, and this could help explain these results. The once per revolution perturbations affect monthly orbital fits to the ranging observations by as much as ten centimeters, but when modelled according to the values of Figure 3, the root mean square fit of each month's data remains below five centimeters, and with this precision it is possible to resolve the vertical components of the selected stations at the centimeter level each month.

Ocean loading at appropriate locations was applied (IERS Standards: McCarthy, 1991), although this semi-diurnal effect would be very small when averaged over the monthly position estimates of stations with adequate sky coverage, but would have an effect on stations which track at favored times of the day (or night). Earth rotation and orientation parameters (EOP) were taken from a global solution in which they were adjusted daily in the J2000 reference system with the effects of dynamic polar motion included, and in which the UT1 time published by the International Earth Rotation Service was fixed for one day of each month to establish a longitude frame. In the global solution the station position for each site was estimated, but its motion was modelled according to Smith et al.(1990), resulting in a consistent reference frame throughout the eight year experimental period. In both the global solution for EOP and the monthly analysis which yielded the height values presented here, the stations' reference system was set by fixing the horizontal position components of Greenbelt (latitude and longitudes) and Maui (latitude). The results for monthly values of station height are reported only if coverage for both of the fiducial stations at Greenbelt and Maui reached a minimum of nine LAGEOS passes, and if there were adequate data from each individual station. A nutation series according to Wahr(1981) was adopted and the effect of solid Earth tides at the stations was also computed according to Wahr(1981)

LASER DATA QUALITY CONTROL

Each of the observatories whose vertical motion was monitored in this analysis contains a well calibrated system that has been in operation since late 1983. During the lifetime of each station, continuous improvements are made to the system through up-grades in hardware and software. Any disturbance at an instrument is monitored with accurate resurveys of the system's eccentricity (optical center with respect to an associated ground marker) as well as of any change in the surveyed distance of the calibration tower used for system delay correction. The eccentricity offsets for the various MOBLAS instruments fielded by the Goddard Space Flight Center are listed in Table 2. They have been retrieved from the Crustal Dynamics Data Information System (CDDIS) in December 1991 and their correctness will directly affect the estimated heights given in Table 1, as well as any measure of vertical motion. The remaining observatories in the network were assumed stationary during the eight year period and their positions refer to the optical axis of each telescope, which is the estimated parameter in our data reduction. Any improved information on eccentricity surveys can be used to efficiently up-date the marker positions, and it is not necessary to repeat the full data reduction process. On the other hand, techniques for direct estimation of station velocity will require accurate eccentricity values at the outset of the analysis to connect the positions of each occupation at a site.

Information concerning calibration characteristics of each system is accessible through the CDDIS, although it is has already been used in the processing of the raw range measurements and is thus embedded in the normal points. As corrections to the calibration procedures are uncovered by subsequent analysis, it is necessary to compensate for any effects that retro-active improvements might exert on station position. Subtle engineering problems in the detection system must be remedied in a pre-processing stage using the original time-of-flight observations, but many of the data corrections can be represented by pass-by-pass or longer term range or timing bias parameters, and the design of our analysis facilitates the incorporation of historical updates using linear shifts based on the partial derivatives of range or clock bias computed in the initial time-consuming computation of normal equations. Several corrections to the released data were required. In particular, range corrections to Arequipa observations were applied: 4 cm to each measurement up to March 1986 to allow for the improved survey of the calibration tower noted in the CDDIS description of this station, as well as another 3 cm until July 1988 at which time improved system delay calibration procedures indicated this offset (Husson, 1988). Range errors of this magnitude would significantly affect any estimates of vertical motion occurring at the rate of a few mm/year, and the possibility of similar anomalies at other locations is closely monitored. The most compelling indication of engineering effects in station position is an abrupt change in station height to a subsequently maintained level: this was clearly seen when earlier, uncorrected Arequipa data was used in quarterly solutions shown in the lower frame of Figure 4. When the height of the station was held fixed at a value estimated over the 13 year data span, the monthly estimates of range bias shown in Figure 4 indicate error in the earlier observations of the correct magnitude.

ANALYSIS OF VERTICAL MEASUREMENTS

The independent monthly values of height at the three stations with the lowest month-to month variation seen in our analysis are given in Figures 5a,b and c. The least significant figures in millimeters of the distance from an average Earth semi-major axis of 6378136.3 m. appear on the vertical scale and the measurements are qualified by error estimates of twice their formal standard deviation based on the final fit of the range observations to each orbital arc. Although the ranges themselves are formally accurate to better than a centimeter, systematic residual signatures of several centimeters in amplitude are observed due to uncompensated errors in force, measurement and Earth orientation models. The effect of atmospheric refraction on the laser ranges is modelled according to Marini and Murray (1973) who assumed a spherically stratified atmosphere based on surface pressure measurements. Herring (1988) has shown that range corrections due the refractivity formula, the zenith range correction and the elevation dependence of the range correction formula should only be a few millimeters at 20 degree elevation angle, which is the lower limit for most of the systems. However, any long term variations in station barometer accuracy or in the effects of lateral gradients in the atmosphere (see Abshire and Gardner,1985) will directly affect the vertical estimates. The SLR systems could thus be used to monitor aberrations in the dry component of atmospheric refraction which would not be separable from the wet component in nearby microwave instruments.

The possibility of errors in the adopted eccentricities must also be considered, particularly for stations which have undergone changes of system occupation, such as Greenbelt, Quincy and Huahine (see Table 2). The system changes at the North American sites coincided with collocation tests which cross-calibrated each instrument's ranging machine as well as its eccentricity. The transportable systems are periodically returned to Greenbelt for up-grades and collocation calibration against MOBLAS-7, but do not usually undergo a collocation test at their working location. The Huahine position shows more variation than the other sites but, because TLRS-2 eccentricity errors are minimized by employing a precise repositioning technique, this behavior is more likely to be due to the influence of the early, less accurate MOBLAS-1 measurements .

Considerable deviation from uniform motion can be noted in the height variation for some stations, and most of the estimated height rates shown in Table 3 are not significant compared to their quoted uncertainties, which are twice the formal standard error based on the fit of the individual values to a straight line. The measures of scatter of the height values about the mean listed in Table 1 are only reduced by a millimeter or two when a linear fit is substituted. The height statistic has been used as a quality control factor in earlier work measuring the horizontal component of motion (see, for example Table 3 of Smith et al.,1990). Considering the scatter of a station's height about a mean (or uniformly moving) value as a measure of the 'quality' of the station's performance, we see that it depends as much on system stability and careful calibration as upon the precision of the observations, and the lower values of height scatter at Greenbelt, Yarragadee and Arequipa testify to the reliability of these instruments.

Post-glacial rebound of the Earth from the melting of continental ice sheets starting roughly 18,000 years ago produces changes in the gravity field as it affects the long-term evolution of the LAGEOS orbit and have been reported by Yoder et al. (1983) and Rubincam (1984). Wagner and McAdoo (1986) present a simple uniform viscosity model for the rate of change of radial position due to post-glacial rebound based on the Ice-2 maps of Wu and Peltier(1983), and this model is complete enough to include all the SLR sites. The values of vertical uplift at each observatory predicted by the model have been taken from Figure 5 of Wagner and McAdoo(1986) and are compared in Table 3 with the height rates estimated from the laser data from the SLR stations, arranged for convenience by tectonic plate. Very little correlation can be seen between the modelled and observed values of up-lift, even in Europe, where the 4 mm/year rate expected from the model is within the detection capability of the SLR systems. On the other hand, neither the model nor the SLR observations taken at Greenbelt can confirm sinking of eastern North America as required by tide gauge data (see Trupin 1991) : the absence of higher degree terms due to the lack of a lithosphere in their treatment has been noted by Wagner and McAdoo and could explain the model results. James and Morgan (1990) have shown in more detail how modelling assumptions of the properties of the lithosphere can cause disagreement with sea level observations, and they have also indicated that horizontal motions due to post-glacial rebound in

North America and Fennoscandia can amount to 4 mm/year from plausible models. This movement is predicted in the Hudson Bay region where vertical movement can amount to over 10 mm/year, and both components are clearly within the resolution capability of a modern SLR system occupying this region in an extended campaign.

It is possible that further investigation of the SLR observations will uncover a source of instrument error which would alias into the vertical component of station position. However, the apparent rate of 4 mm/year observed at Arequipa is large enough that no SLR analysis should assume a stationary vertical component and expect accurate baseline measurements to distant stations. Only explicit separation from the vertical component by considering geodesic lengths will allow the definition of accurate horizontal motion.

CONCLUSIONS

The stability of the radial component of position at the strongest SLR observatories in an eight year time span suggests that vertical motion is bounded by 2 or 3 mm/year and this analysis does not confirm variations suggested by models of post-glacial rebound. Periodic signatures apparent in the height results may represent seasonal variations of a geophysical nature, but do not produce significant long term trends. These accurate estimates of station height can help in the calibration of satellite altimeters as well as to establish scale for positioning techniques which degrade as a function of distance on a global scale, such as GPS campaigns in close proximity to the SLR Observatories. The data quality control which must be exercised to retain the full scaling accuracy of the laser ranges is not so stringent in the analysis of GPS networks as they benefit from strong orbital geometry when multiple satellites are simultaneously tracked. On the other hand, accurate relative position measurements of each instrument's reception center from a ground marker is critical in both space techniques and must be carefully monitored. The capability with which the Global Laser Tracking Network can control vertical scale will grow with the increased number of retro-reflector-carrying satellites expected to be in high Earth orbit in the next few years. As observations from LAGEOS 2 are supplemented by concentrated tracking of the currently orbiting ETALON spacecraft, time resolution of any subtle vertical motion should also be improved.

REFERENCES

Abshire,J.B. and C.S.Gardner,"Atmospheric Refractivity Corrections in Satellite Laser Ranging", IEEE Trans. on Geosc. and Rem. Sense. GE-23, 1985

Afonso, G,F.Barlier,M.Carpino,P.Farinella,F.Mignard,M.Milani and A.M..Nobili," Orbital Effects of LAGEOS Seasons and Eclipses", Ann.Geophys.A 7(5),501-514,1989

Anselmo,L.,B.Bertotti,P.Farinella,A.Milani and A.M.Nobili,"Orbital Perturbations due to Radiation Pressure for a Spacecraft of Complex Shape", Celest. Mech. 29,27,1983

Bertotti,B.,and L.Iess,"The Rotation of LAGEOS", J.Geophys.Res., 96,2431-2440, 1991

Christodoulidis,D.C., D.E.Smith, R.Kolenkiewicz, S.M.Klosko, M.H.Torrence and P.J.Dunn,"Observing Tectonic Plate Motions and Deformations from Satellite Laser Ranging", J.Geophys.Res., 90(B11),9249-9263,1985

Degnan,J.J.,"Satellite Laser Ranging: Current Status and Future Prospects", IEEE Trans. on Geosc. and Rem. Sense. GE-23, 1985

Eanes,R.J. and M.M. Watkins,"Temporal Variability of Earth's Gravitational Field from Satellite Laser Ranging Observations", XX Gen. Ass. IUGG Symp. No.3,Vienna,1991

Fitzmaurice,M.W.,P.O.Minott,J.B.Abshire and H.E.Rowe,"Prelaunch Testing of the Laser Geodynamic Satellite (LAGEOS)", NASA Tech. Paper 1062,1977

Frey H.V. and J.M.Bosworth,"Measuring Contemporary Crustal Motions: NASA's Crustal Dynamics Project", Earthqu. and Volc. 20(3), 1988

Husson,V.S.,"First Six Month Data Processing Report",BFEC Report, October 1988

James,T.S.,and W.J.Morgan,"Horizontal Motions due to Post-Glacial Rebound", Geo. R.Lett. 17(7) 1990

Lerch,F.J," Geopotential Models of the Earth from Satellite Tracking, Altimeter and Surface Gravity Observations: GEM-T3 and GEM-T3S", NASA TM 104555, 1992

McCarthy D.D.(ed.), IERS Standards(1989), IERS Tech. Note 3, Central Bureau of IERS, Observatoire de Paris, 1989

Putney,B.,R.Kolenkiewicz,D.Smith,P.Dunn and M.H.Torrence,"Precision Orbit Determination at the NASA Goddard Space Flight Center", Adv. Space Res., 10(3),197-203, 1990

Ries,J.C.,R.J.Eanes,C.K.Shum and M.M.Watkins,"Progress in the Determination of the Gravitational Coefficient of the Earth", in press,1992

Rubincam,D.P.,"Postglacial Rebound Observed by LAGEOS and the Effective Viscosity of the Lower Mantle", J.Geophys.Res., 89(B2),1077-1087, 1984

Rubincam D.P.,"Drag on the LAGEOS Satellite",J. Geophys.Res., 95,4881-4886,1990

Scharoo,R.,K.F.Wakker,B.A.C.Ambrosius and R.Noomen,"On the Along-track Acceleration of the LAGEOS Satellite", J.Geophys.Res., 96,729-740, 1991

Smith,D.E.,R.Kolenkiewicz,P.J.Dunn,J.W.Robbins,M.H.Torrence,S.M.Klosko and R.G.Williamson,"Tectonic Motion and Deformation from Satellite Laser Ranging to LAGEOS", J.Geophys.Res., 95(B13),22013-22041, 1990

Trupin A.S.," The Effect of Global Change and Long Period Tides on the Earth's Rotation and Gravitational Potential", U. Col. Ph.D. Thesis, 1991

Wagner,C.A. and McAdoo,D.C.,"Time Variation in the Earth's Gravity Field Detectable With GRM Intersatellite Tracking",J.Geophys.Res. 91(B8), July,1986

Wahr,J.M.,"The Forced Nutations of an Ellipsoidal Rotating, Elastic and Oceanless Earth", Geophys.J.R.Astron.Soc.64, 1981

Wu, P.,and Peltier,W.P.," Glacial Isostatic Adjustment and the Free Air Gravity Anomaly as a Constraint on Deep Mantle Viscosity", Geophys. J. R. Astron. Soc.74, 1983

Yoder,C.F.,J.G.Williams,J.O.Dickey,B.E.Schutz,R.J.Eanes and B.D.Tapley,"Secular Variation of Earth's Gravitational J2 Coefficient from LAGEOS and Non-tidal Acceleration of Earth Rotation", Nature 303, 1983

TABLE 1 : STATION POSITIONS

		LATITUDE DEG MNSEC	LONGITUDE DEG MNSEC	HEIGHT METERS	ST.ERR. MILLIMETERS	ST.DEV MILLIMETERS	NO. MONTHS
GREENBELT	7105	39 1 14	283 10 20	19.931	2	16	69
QUINCY	7109	39 58 30	239 3 19	1107.119	2	18	67
MON.PEAK	7110	32 53 30	243 34 39	1839.746	2	20	73
YARAGADEE	7090	-29 2 47	115 20 48	242.080	2	16	69
HUAHINE	7123	-16 44 1	208 57 32	46.110	5	23	22
AREQUIPA	7907	-16 27 57	288 30 25	2492.945	2	17	52
MATERA	7939	40 38 56	16 42 17	536.551	2	19	60
WETZEL	7834	49 8 42	12 52 41	661.842	4	24	45
GRAZ	7839	47 4 2	15 29 36	540.125	3	20	55
RGO	7840	50 52 3	20 10	76.114	3	21	69
SIMOSATO	7838	33 34 40	135 56 13	100.175	4	25	51

TABLE 2 : ECCENTRICITY OFFSETS

			START	STOP	N(mm)	E(mm)	UP(mm)
GREENBELT	7105	MOBLAS-7	84 1 1	84 3 22	16	-26	3169
			84 3 22	85 7 29	17	-32	3169
			85 7 29	89 10 12	17	-31	3168
			89 10 12	90 7 25	35	-40	3162
			90 7 25	91 12 31	-14	-33	3153
	7918	TLRS-4	90 4 6	90 7 23	-7	-5	2613
QUINCY	7109	MOBLAS-8	84 1 1	86 9 18	-29	11	3124
			86 9 26	91 3 17	-27	12	3138
		TLRS-4	91 3 19	91 8 19	-5	0	2651
		MOBLAS-8	91 11 18	91 12 11	-19	5	3184
			91 12 12	91 12 31	-35	-3	3184
MON.PEAK	7110	MOBLAS-4	84 1 1	88 4 30	-33	-15	3210
			88 4 30	91 12 31	-33	-16	3213
YARAGADEE	7090	MOBLAS-5	84 1 1	87 8 13	3	11	3185
			87 8 13	91 12 31	3	10	3177
HUAHINE	7121	MOBLAS-1	84 1 1	86 3 13	8	1	3662
	7123	TLRS-2	87 7 14	87 10 8	0	0	1453
			88 3 16	88 9 1	0	0	1437
			89 4 24	89 9 3	0	0	1482
			90 3 15	90 8 20	-1	3	1459
			91 4 5	91 9 4	-2	4	1482

GROUND MARKER DISTANCES

	X(mm)	Y(mm)	Z(mm)
7105 TO 7918	-14419	5137	9457
7121 TO 7123	1458	807	501

TABLE 3 : COMPARISON WITH POST-GLACIAL REBOUND MODEL

TECTONIC PLATE	STATION	MODEL	OBSERVED	
N. AMERICAN	GREENBELT	3	1.7	+/-2 mm/year
	QUINCY	3	1.5	2
PACIFIC	MON.PEAK	1	2.6	2
	HUAHINE	1	3.2	4
AFRICAN	MATERA	1	2.3	2
EURASIAN	WETZEL	4	-1.5	3
	GRAZ	4	.9	2
	RGO	4	-.2	2
AUSTRO-INDIAN	YARAGADEE	1	1.4	2
S. AMERICAN	AREQUIPA	-2	4.1	2
UNKNOWN	SIMOSATO	-3	2.2	4

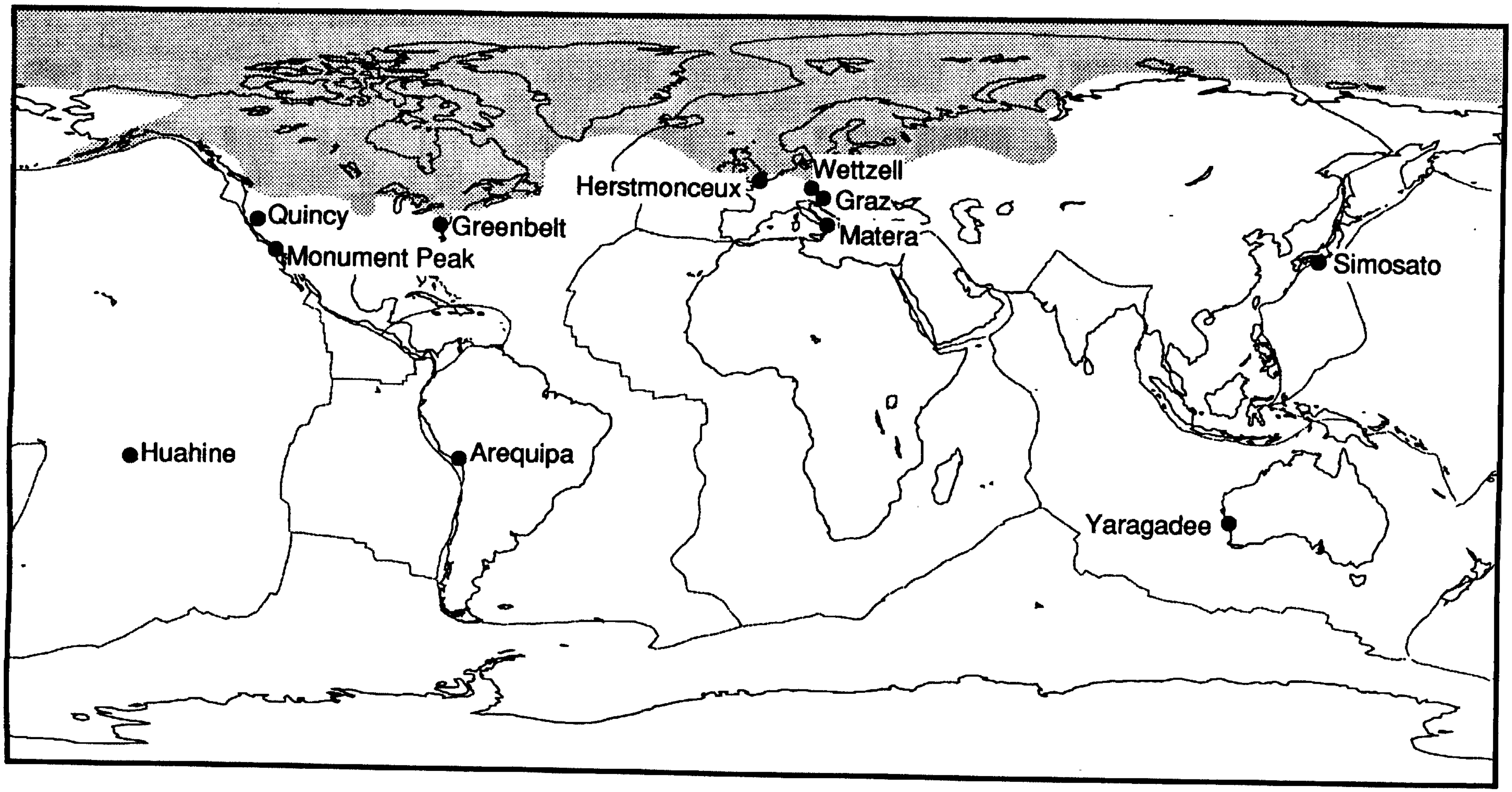

Figure 1 : A world map showing the selected stations and Tectonic and Ice Sheet Boundaries.

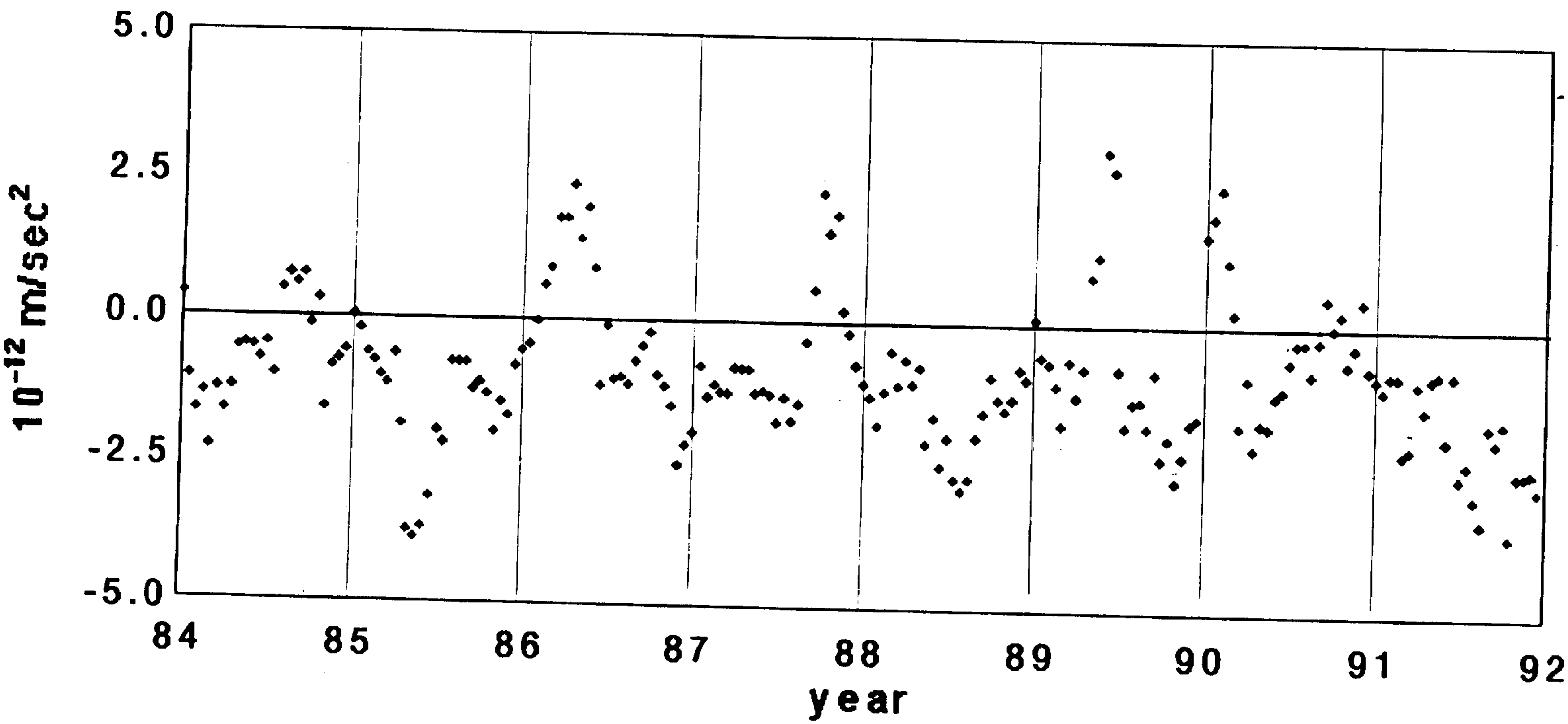

Figure 2 : Semi-monthly values of direct estimates of along-track accelerations.

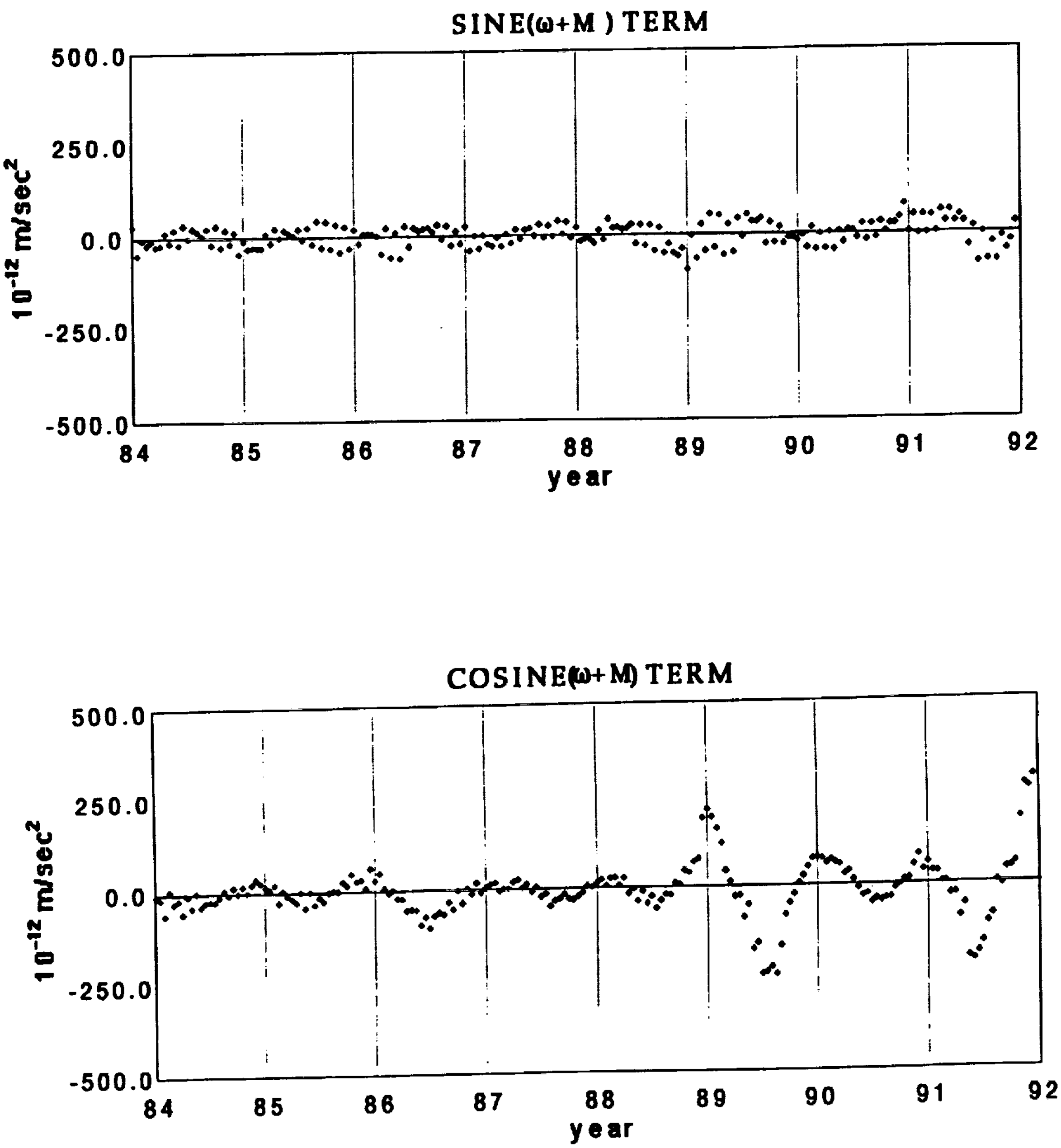

Figure 3 : Semi-monthly values of the once-per revolution acceleration

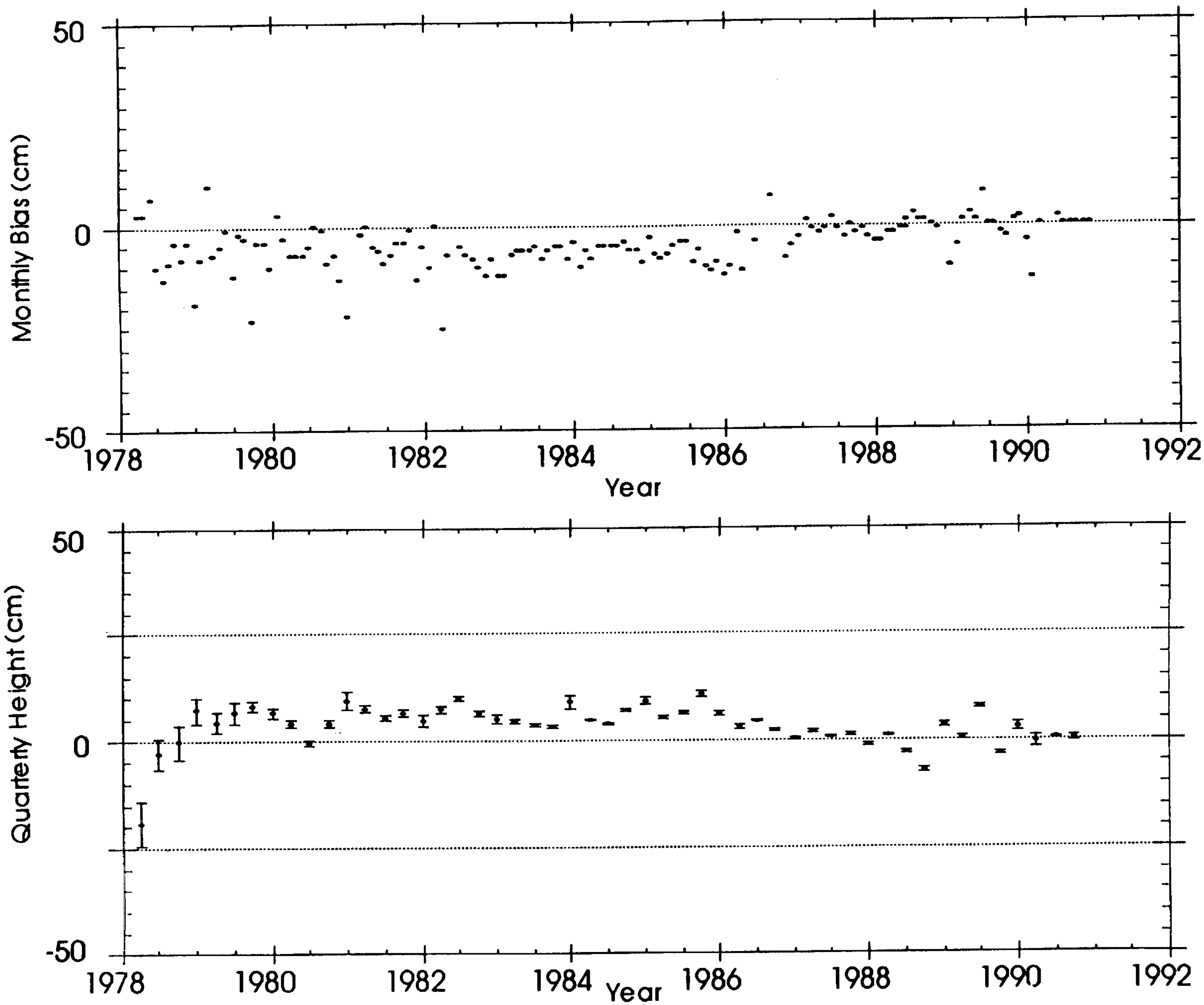

Figure 4 : Arequipa Range Bias Estimates and Equivalent Station Height Variations

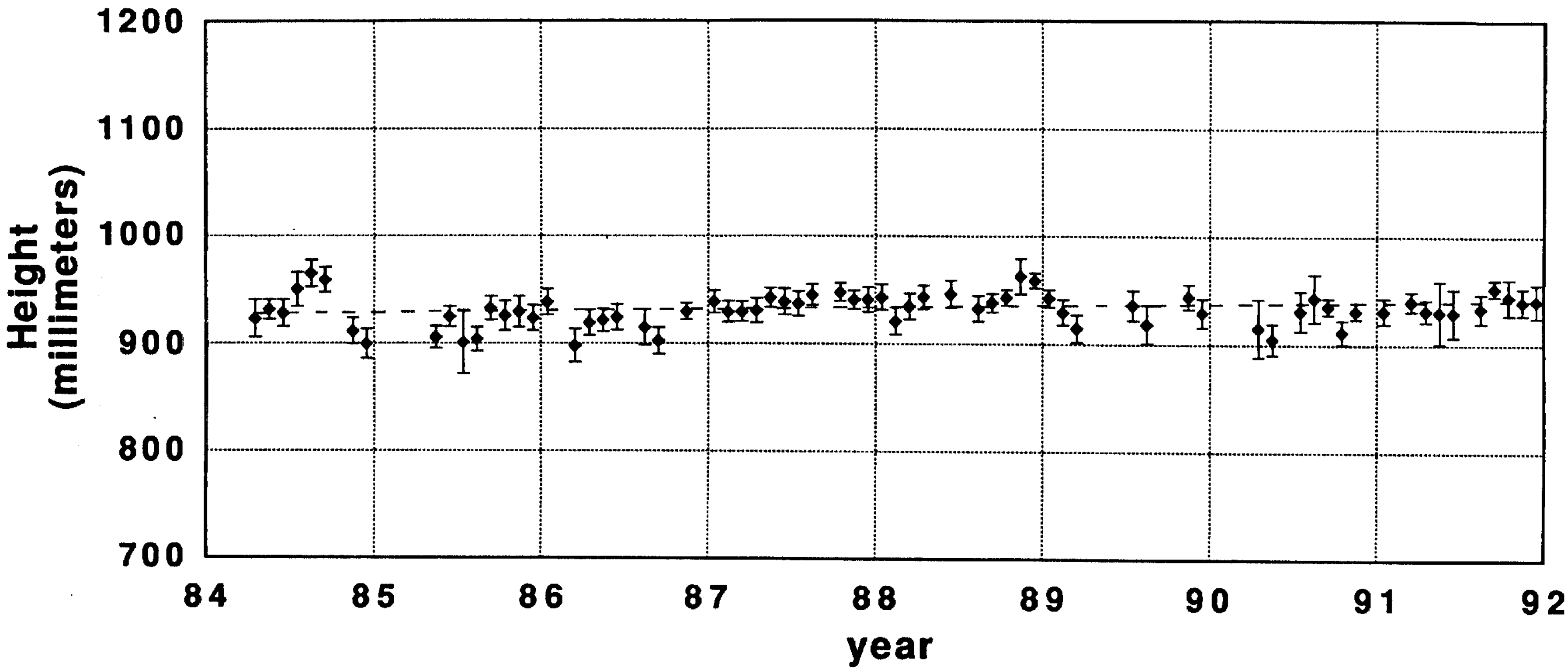

Figure 5a : Monthly estimates of the height of Greenbelt

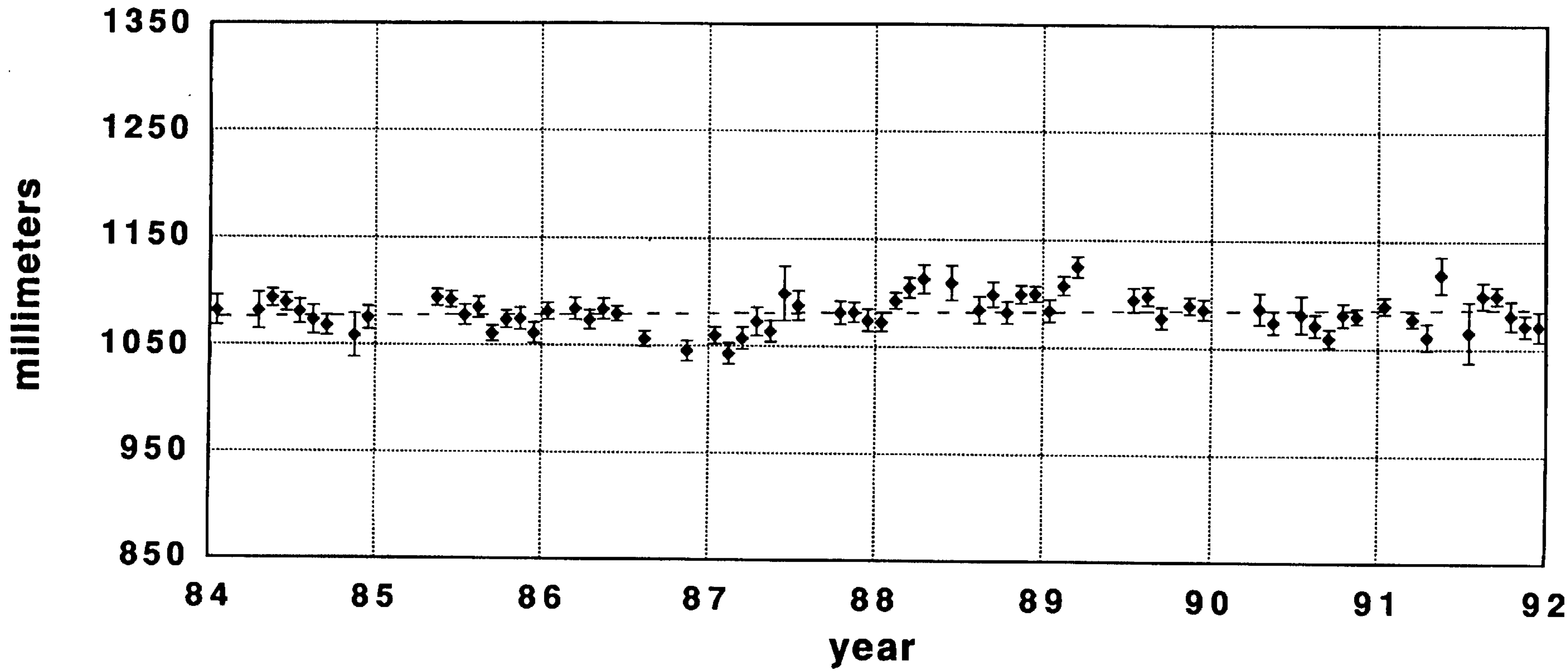

Figure 5b : Monthly estimates of the height of Yarragadee

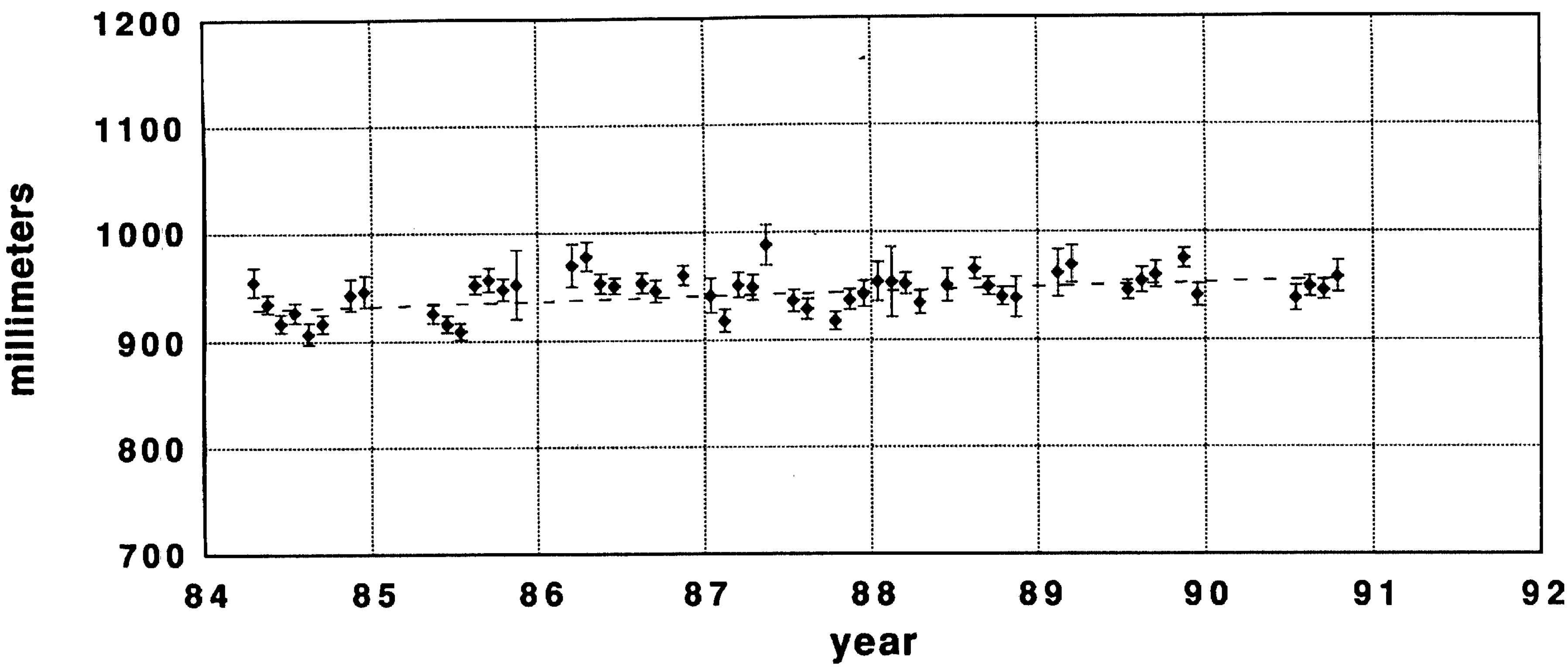

Figure 5c : Monthly Estimates of the height of Arequipa